Costs of the Kyoto Protocol: A New Assessment

An Energy Laboratory analysis suggests that enforcing the Kyoto Protocol may not be as expensive as most people think—as long as countries follow the intended guidelines. Most analyses consider the cost of reducing only carbon dioxide (CO2) emissions from fossil fuel use. But the protocol also recognizes reductions in other greenhouse gases (GHGs). According to the MIT analysis, taking advantage of opportunities to reduce those gases as well as CO2 can cut the cost of compliance in half. The protocol puts all gases on a common basis by using “global warming potentials” (GWPs) to weight the value of any emission reduction according to the gas’s warming ability and lifetime in the atmosphere. In theory, then, meeting the Kyoto targets by cutting only CO2 or by cutting a combination of gases weighted using their GWPs should give the same climate impacts. To test the validity of the GWPs, the researchers used MIT’s integrated atmospheric chemistry, climate, and ecosystem model to simulate the effects of the CO2-only and the multi-gas strategies for meeting the Kyoto requirements. The predicted global warming was similar for the two strategies. However, substantial differences appeared when the two strategies were used in response to a hypothetical policy involving deeper emissions cuts and participation by developing countries—assumptions that increase the role played by non-CO2 emissions. The GWPs are so flawed that such a stringent policy may or may not give the intended climate results, depending on which types of emissions are cut. The MIT team is now rethinking how to value emissions reductions, including considerations such as the timing of the avoided damage and the importance of protecting future generations from long-lived GHGs put into the atmosphere now.

In 1997, more than 80 countries signed the Kyoto Protocol on Climate Change. In it, the developed countries including Russia and the European economies in transition agreed to cut their emissions of GHGs to 5% below 1990 levels by the 2008–2012 period. Few countries have yet ratified the agreement, and it may not go into effect as anticipated. The basic targets and timetables laid out in the agreement still provide a useful set of assumptions for understanding the costs of climate policy. One reason for the reluctance to ratify Kyoto is that projections of the high cost of implementing it abound. For the most part, cost analyses have focused exclusively on reductions of CO2 emissions from fossil fuel use—

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<tbody>
<tr>
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<td>CO2 only</td>
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<td>$258</td>
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<tr>
<td>Multi-gas</td>
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<td>724</td>
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<td>724</td>
<td>$360</td>
<td>$86</td>
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This table shows Energy Laboratory estimates of emissions reduction targets, marginal costs, and total annual costs for the United States in 2010 of fulfilling its requirements under the Kyoto Protocol. Three possible strategies are considered: setting a reduction target at 7% below 1990 levels based on carbon dioxide (CO2) emissions only; setting the 7% reduction target using Kyoto’s “multi-gas” approach (a mix of greenhouse gases plus forest sinks) and achieving the target by reducing CO2 emissions only; and setting and achieving the target based on the multi-gas approach. (The estimates are derived from the curves shown on page 3.) The researchers conclude that ignoring opportunities to reduce non-CO2 gases and to enhance forest sinks would double the total annual cost of implementing the Kyoto Protocol.
a familiar area due to the intensive energy modeling and analysis of the 1970s. But the protocol actually addresses emissions not only of CO₂ but also of other less-familiar GHGs—methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons, and sulfur hexafluoride—which come from such diverse sources as landfills, aluminum production, livestock, and electrical switchgear. Also recognized are measures to increase CO₂ “sinks,” which include forestation and other land-use changes that will increase the amount of CO₂ absorbed from the atmosphere. Researchers are generally aware that their analyses should include the other GHGs and forest sinks, but most have believed that the impact on Kyoto’s estimated cost would be small.

To check that assumption, Dr. John M. Reilly, Professor Ronald G. Prinn, and their colleagues at MIT and at the Marine Biological Laboratory at Woods Hole have made the first comprehensive assessment of the consequences of the multi-gas approach to implementing the Kyoto Protocol. They determined the cost of meeting the protocol’s requirements in two ways: first by reducing only CO₂ and then by reducing a mix of all six GHGs in the least costly way. (All analyses of multi-gas reductions include forest sinks as one component.) They then examined the impacts of those strategies on future global climate.

To perform their cost assessment, the researchers used their Emissions Prediction and Policy Assessment (EPPA) model, which analyzes economic activities and associated emissions in terms of sectors, technologies, and regions. They present their results in “marginal abatement curves” that show the cost of an additional one-ton reduction in emissions at various levels of abatement.

Their findings for the United States appear in the figure on page 3. The higher curve shows the cost in 1995 dollars of eliminating a ton of carbon emissions if only CO₂ emissions from fossil fuel use are considered. (One ton of carbon corresponds to 3.67 tons of CO₂.) The lower curve shows the same information for emissions of all the Kyoto GHGs, each adjusted according to its contribution to atmospheric warming relative to CO₂. As expected, in both curves the cost of eliminating a ton of carbon emissions increases as more reduction occurs. (One performs the least expensive reductions first.) Including more GHGs expands the available set of abatement opportunities, so cost at a given level of abatement is lower for the multi-gas strategy.

Examining costs at selected levels of abatement provides some interesting insights. The protocol calls for the United States to reduce its GHG emissions to 7% below its 1990 level by 2008–2012. If the US had to reduce CO₂ by that percentage by 2010 (the selected ending date), the required reduction would be 645 megaton carbon equivalent (Mtce), marked on the figure as “RR1.” (See also the summary table on page 1.) At that level, the marginal cost of CO₂ reduction (the cost of preventing the last ton of carbon from escaping) would be $258/tce (P1). The total annual abatement cost (measured by the area below the curve) would be $61 billion.

In contrast, if the United States had to reduce its 1990 emissions of all six Kyoto gases by 7%, the required reduction would be 724 Mtce (RR2). However, because of the added abatement opportunities, the marginal cost would be only $176/tce (P2) and the total annual cost only $43 billion. Thus, including a variety of GHGs provides more environmental benefit for less investment.

Looked at another way, the figure carries a clear warning. If the United States tried to achieve the Kyoto-specified abatement level of 724 Mtce by cutting only CO₂ from fossil fuel use, the marginal cost of eliminating those CO₂ emissions would be $360/tce (P3), and the total annual abatement cost would be $86 billion. Thus, the nation would pay twice as much to meet its Kyoto targets if it ignored opportunities to control emissions of all the named GHGs.

Using their EPPA model, the researchers also looked at emissions-reduction costs for the “Annex B” countries (those subject to emissions limits, namely, the members of the Organization for Economic Cooperation and Development as of 1990, plus Eastern Europe and most of the former Soviet Union). The calculated costs vary from country to country, but in every case they are minimized by pursuing multi-gas reductions. For Annex B as a whole, the cost of meeting the protocol’s targets is about $174 billion if only CO₂ abatement is undertaken and about half that much if emissions of all gases are cut and forest sinks are used. Thus, low-cost opportunities to cut emissions other than CO₂ are more abundant—and more critical—than most experts have believed.

What about the climatic impacts of the emissions-control strategies? Reductions in emissions of the various gases cannot be compared on a ton-for-ton basis because the gases have varying abilities to capture heat and varying lifetimes in the atmosphere. The protocol therefore includes a set of
indexes—the GWPs—that reflect each gas’s potential for global warming over a set period of time relative to CO₂. Adjustments based on those GWPs are intended to put reductions of all gases on a common basis. If the GWPs laid out in the protocol do their job well, the impact on climate will be identical whether the Kyoto target is met by reducing CO₂ or a mix of gases. But if, for example, the GWPs presented in the protocol overvalue cuts in a given gas, countries may meet their reduction targets without eliciting the expected climatic effect.

To test the accuracy of the GWPs, the researchers used their “Integrated Global System Model” (IGSM) to estimate the consequences for the atmosphere, climate, and ecosystems of using different control strategies. Developed over many years by an interdisciplinary research team, the IGSM includes components that simulate economic growth and associated emissions (the EPPA model); complex feedbacks among ecosystems, atmosphere, and oceans; chemical interactions among gases in the atmosphere; the impact of climate change itself on various processes; the roles of carbon monoxide and nitrogen oxides; and the cooling effect of aerosols.

The first analysis focused on the Kyoto commitments for all of the Annex B countries, extended unchanged to the end of 2100. The researchers calculated the climate and ecosystem effects, first assuming only CO₂ emissions are controlled and then assuming multi-gas controls. Both cases concluded that temperatures would increase by about 2.4°C between 1990 and 2100. The predictions are consistent, so the GWPs appear to be effective in calculating trade-offs among emissions in the various gases.
However, climate change experts generally agree that more dramatic steps are needed to stabilize atmospheric concentrations of GHGs in the future. Therefore, the MIT team devised a hypothetical policy requiring developed countries to achieve much larger cuts and developing countries to start a comparable program of cuts beginning in 2025. Meeting that more-stringent policy with a CO₂-only strategy produced an estimated increase in temperature between 1990 and 2100 of 1.1°C. Assuming a multi-gas strategy yielded a temperature increase of only 0.5°C. Thus, the projected climatic impacts of the two strategies differ substantially when the cuts are deeper and the developing countries are involved—changes that increase the importance of the role played by gases other than CO₂. Again, if the GWPs in the protocol are accurate, the projected temperature increases would be the same. Instead, they are different, and the difference is large enough to have important policy consequences: if policymakers take serious steps toward stabilizing the climate, the GWPs in the Kyoto Protocol will not provide a sound basis on which to set targets, credit emissions reductions, and value the emissions permits that, under the protocol, could be traded internationally.

How can the GWPs be improved? To clarify the issues and trade-offs involved, the MIT researchers used the IGSM to calculate GWPs under a variety of assumptions. Not surprisingly, assuming different time horizons gives very different outcomes. The GWPs in the protocol are based on the accumulated climatic impacts of a unit of an emitted GHG over the next 100 years. That time period is fine for some gases. Methane, for example, lasts only about a decade. But some gases last for many thousands of years, and their impacts beyond 100 years are lost. Allowing for interactions among gases in the atmosphere also changes the GWPs. IGSM analyses show that the climatic impact of a given GHG is directly influenced by concentrations of other gases. Indeed, large errors result from ignoring the interactive and climatic effects of non-Kyoto gases such as carbon monoxide, nitrogen oxides, and sulfur dioxide. And because the concentrations of other important gases are not constant over time, the GWP for a given GHG is likely to change over time.

Other factors must also be considered in deciding how to value cuts in various emissions. Controlling short-lived gases will yield climatic benefits sooner than controlling long-lived ones will. Cuts in short-lived GHGs are most valuable if we believe that the dangers from climate change are imminent. But if the danger of global warming is not immediate, cutting long-lived GHGs is a higher priority. Eliminating gases that last for thousands of years from today’s emissions provides a benefit essentially forever, whereas today’s emissions of short-lived gases like methane will be gone from the atmosphere in a few decades. Many people also place a high value on protecting future generations from harm, regardless of the source; and this consideration favors controlling the very long-lived gases. Finally, reductions in some emissions may bring “ancillary” benefits. In particular, the MIT analyses show that reducing emissions of certain GHGs also reduces emissions of critical urban air pollutants. (Cutting down fossil fuel use eliminates all sorts of emissions.) The researchers thus stress the need to consider global, regional, and local environmental concerns simultaneously when calculating the cost and effectiveness of any type of emissions-control strategy.

The researchers’ analyses reveal serious shortcomings in current climate change policy—both in its design and in its likely implementation. Making improvements will require substantial advances in both scientific and economic understanding. Critical needs are better modeling capabilities; credible inventories of emissions of all GHGs, especially in the developing world; and a sound basis on which to extend analyses beyond 2010. In the near term, the MIT researchers recommend that the scientific community develop the best possible GWPs for the short-lived GHGs and that mechanisms be established that encourage countries to reduce or trade emissions of those gases to meet their Kyoto targets. However, they question whether gases that last for thousands of years should be part of such a trading system because of the difficulty of accurately comparing them to short-lived gases. An alternative policy would focus on simply reducing emissions of those long-lived gases to the lowest possible level.

John M. Reilly is associate director for research at the MIT Joint Program on the Science and Policy of Global Change. Ronald G. Prinn is the TEPCO Professor of Atmospheric Chemistry, head of the Department of Earth, Atmospheric, and Planetary Sciences, and co-director of the Joint Program. This research was funded by the MIT Joint Program on the Science and Policy of Global Change. Further information can be found in references 1–3.
Running Buses on Hydrogen Fuel Cells: Barriers and Opportunities

Vehicles running on fuel cells fed by hydrogen could be ideal environmentally for crowded cities: they are quiet and clean, emitting none of the air pollutants that now plague urban areas. And emissions of greenhouse gases could be eliminated as well if the hydrogen were made using carbon-free sources such as solar power. But figuring out how to deliver hydrogen to private vehicles is a daunting problem, given today’s fuel handling and storage technologies. Energy Laboratory researchers have looked at a more manageable application of this technology: in fleets of buses. They focused on a demonstration in which the Sunline Transit Agency in Los Angeles will gradually switch its buses from compressed natural gas engines to fuel cells, powered first by commercially provided liquid hydrogen and subsequently by compressed hydrogen gas that Sunline itself will manufacture from natural gas. This commercial experience will help clarify the issues involved in producing, handling, and storing hydrogen; maintaining and operating vehicles; and providing a given level of service. The MIT assessment identifies many of the practical hurdles Sunline must overcome, from setting up its hydrogen fueling station to retraining its managers and operators. Broader issues include the public’s perception of hydrogen fuel as dangerous; potentially high costs; and still-evolving safety, zoning, and other regulations. Whether hydrogen will become the clean transportation fuel of the future remains to be seen. But if all goes as planned, Sunline’s customers will get a first taste of the potential benefits of this technology: clean, quiet buses that get them where they need to go.

In the United States, on-road vehicles emit more than a quarter of all domestic carbon dioxide (CO₂) emissions as well as large quantities of local emissions including hydrocarbons, nitrogen oxides, and particulates. One way to eliminate those local emissions could be to run cars on fuel cells fed by hydrogen. Combining hydrogen with oxygen in a fuel cell produces electricity, a bit of heat, and water. Unfortunately, pure hydrogen does not occur in nature; so getting hydrogen for fuel requires separating it from plentiful compounds such as natural gas or water. If the hydrogen is made from natural gas, CO₂ emissions could drop by up to 25% compared to today’s gasoline vehicles. And if it is made from non-carbon sources or using carbon capture and sequestration technologies, CO₂ emissions are eliminated. (The main competing “zero-emission vehicle” technology is the electric car, but battery storage of electricity is cumbersome and limits the distance a vehicle can travel between refueling stops.)

Automakers have demonstrated prototype vehicles that run on hydrogen fuel cells, but distributing hydrogen to today’s drivers seems an overwhelming problem. Using hydrogen fuel cell technology in fleets of commercial vehicles such as buses might make more sense. A centralized hydrogen fueling station could serve an entire fleet of buses; a single fleet manager could oversee the maintenance of the fleet and supporting facilities; and the service routes for the vehicles could be carefully planned to fit their capabilities.

Given the many unknowns in such an undertaking, real-world testing is a necessity. Graduate student Jane Brydges working with Dr. Elisabeth M. Drake assessed the challenges involved in designing and implementing a fleet demonstration. What practical steps are required to develop and support a system of hydrogen fuel cell buses? And what barriers must be overcome for the fleet test to occur? Answering those questions should shed light on the problems involved in the wider adoption of hydrogen in commercial or even passenger vehicles.

In their assessment, the researchers focused on a demonstration planned by Sunline Transit Agency, a company that operates a fleet of 50 buses in the Coachella Valley near Los Angeles, California. The Los Angeles area is highly motivated to test alternative transportation systems because air pollution is severe, road travel is critical to the city’s lifestyle, and clean air regulations are unusually stringent. Within three years, a fraction of all buses must be zero-emissions vehicles, and fuel cell buses carrying their own hydrogen supply will qualify—and will be quiet as well.

In reviewing various demonstrations of alternative fuels, the MIT researchers concluded that one key to success is a company’s commitment. Sunline has a strong history of such commitment. In 1994, it replaced its entire aging diesel fleet with compressed natural gas (CNG) vehicles. It bought equipment, retrained its personnel, and worked closely with the community. Operating costs declined, ridership increased, and emissions of local pollutants dropped. Now Sunline’s managers are planning to reduce local pollutant emissions still further by switching at least some of their CNG buses to hydrogen fuel cells by 2005.

To expedite the switch, Sunline will begin by trucking in liquid hydrogen from a nearby chemical plant and retrofitting or replacing a few buses to use the new fuel. Hydrogen will be stored on the roof of the vehicle in superinsulated storage tanks at slightly above atmospheric pressure and at low temperature (about 20 K) to keep it in liquid form. (See the table on page 6 for information about various onboard fuel storage options.) The company will develop special procedures and facilities for refueling the buses, for performing maintenance and repairs, and for operating the buses in a safe manner.
Special handling is required because of the nature of hydrogen. Some of the stored liquid continuously boils off; so when the bus is idle or shut off, hydrogen gas accumulates inside the tank. Because molecules of hydrogen are tiny, they will readily leak through seals in tanks and pipes. But preventing their escape is critical because hydrogen is flammable over a wide range of concentrations in the air (see the table). The safest approach is therefore to purge the gas that forms inside the tank to prevent excessive accumulation. Because hydrogen is odorless and colorless, hydrogen detectors are required at the fueling station and on the buses. And knowledgeable, well-trained personnel must perform all the handling of the hydrogen, including refueling.

Much can be learned from such a demonstration. However, commercial supplies of liquid hydrogen are limited and expensive. Therefore, Sunline plans to manufacture its own hydrogen fuel as soon as it can. As part of the assessment, Ms. Brydges and Dr. Drake reviewed the pros and cons of various approaches Sunline could take.

Again, for an essentially emissions-free vehicle, the hydrogen would have to be derived from renewable energy sources. Solar or wind power, for example, could provide energy to electrolysis machines that would split water into hydrogen and oxygen. Or the hydrogen could be made from traditional fuels, with carbon emissions captured and sequestered. But large technical and economic challenges must be overcome before such operations are feasible at a commercial scale.

Another transitional option is to pump liquid fuels such as gasoline or methanol into the vehicle storage tank and to put on board each vehicle a “reformer”—a chemical reactor that transforms the liquid fuel into hydrogen for the fuel cell and exhausts the carbon as CO₂. The infrastructure for producing and distributing gasoline already exists. However, gasoline is a complex mixture; and designing an effective onboard reformer is difficult. Methanol is simpler chemically, and it can be processed more easily and efficiently. But a new infrastructure would have to be established to distribute this new fuel. In addition, reforming either gasoline or methanol to hydrogen gives off almost as much carbon as is saved by using the more efficient fuel cell technology. Net CO₂ emissions are therefore about the same as CO₂ emissions from burning gasoline or methanol in an advanced internal combustion engine.

Another potential source of hydrogen—natural gas—offers several advantages. Natural gas is plentiful in most parts of North America; and the system of pipelines for transporting it is extensive, safe, and familiar to the public. Natural gas contains few contaminants, and reforming it is an established technology.

In its demonstration, Sunline plans to explore the natural gas option. It will obtain natural gas from the existing pipeline network; reform it to hydrogen gas and compress the hydrogen at a central fueling station; and load the

### Comparison of Options for Onboard Storage of Fuel

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<th>Hydrogen</th>
<th>Natural Gas (methane)</th>
<th>Gasoline</th>
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<tr>
<td><strong>Storage temperature (approx.)</strong></td>
<td>20 K ambient</td>
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<td><strong>Storage pressure (atm)</strong></td>
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<td>?</td>
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<tr>
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<td>400*</td>
<td>300+</td>
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<td><strong>Weight of fuel system: fuel weight (approx.)</strong></td>
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<td>30:1</td>
<td>20+:1</td>
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<td><strong>On-the-road carbon emissions (gC/MJ fuel energy)</strong></td>
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<td>20</td>
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<td>1.5</td>
<td>1</td>
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*Carbon-fiber wrapped aluminum
compressed hydrogen into storage tanks onboard the bus. Emissions of local pollutants and CO₂ will be about the same as from the current CNG-fueled system; but the emissions will be generated not on the bus but at the central fueling station, where the local emissions can more easily be controlled.

However, storing and moving the hydrogen gas pose problems. Systems and techniques designed for natural gas can be used, but some adaptations must be made. Hydrogen gas is only an eighth as dense as natural gas, so higher compression is needed to store a useful amount of fuel in a tank of a reasonable size. CNG is usually stored at pressures around 200 atmospheres; hydrogen gas would be stored at more than 300 atmospheres. Using hydrogen gas rather than CNG therefore requires better seals, monitors, meters, and other special equipment. The need for well-trained managers and operators is critical. An important question to be addressed is whether a fuel tank of acceptable size and weight can store enough hydrogen gas to power a bus on its daily service run. (Storage of hydrogen gas in metal hydrides has been widely studied but is currently unsuitable for buses because of the weight and cost.)

Summarizing their general findings, the Energy Laboratory researchers identified several potential barriers and concerns, both for a demonstration within five years and for longer-term adoption of the hydrogen fuel cell. One major problem is public acceptance. People are wary of hydrogen. The explosion of the Hindenburg, a hydrogen-filled zeppelin, some 60 years ago created a lingering public perception of hydrogen as a dangerous, flammable, and explosive fuel. In fact, hydrogen does ignite easily. Even static electricity can cause ignition. However, hydrogen also disperses unusually readily, so inadvertent ignition is a problem only in confined spaces. (On the Hindenburg, hydrogen probably did cause ignition; but the subsequent burning was due to the construction materials.) Rigorous testing has led many experts to believe that hydrogen is no more dangerous than any other fuel as long as equipment and procedures suited to its particular characteristics are used. Demonstration programs must convince the public that hydrogen is at least as safe as conventional gasoline is. And preventing any accident or malfunction during the demonstration is crucial, as a single mishap could confirm the public's view of hydrogen as being unacceptably dangerous.

Another significant barrier to the introduction of hydrogen fuel cell buses is cost. Estimates suggest that hydrogen would cost several times more per mile driven than gasoline does. The capital cost of making the change is uncertain, even at the local level. Interested fleet operators would need to obtain financial support through government subsidies or private and public partnerships, some of which are already established. The ongoing regulatory process is also a concern. Standards already exist for connectors, high-pressure storage tanks, liquid storage tanks, and fuel specifications. But regulators are still working on appropriate building and fire safety codes, schedules for vehicle maintenance and inspection, requirements for training managers and operators, and standards and zoning requirements for siting hydrogen refueling stations and for transporting hydrogen fuel. Until such regulations are in place, companies will have difficulty designing demonstrations that are persuasive for long-term implementation.

In the near term, the focus on hydrogen fuel cells is motivated largely by the need to reduce urban air pollution. However, in the long term, society may have to dramatically reduce carbon emissions. If so, the two likely candidates for transportation fuels are hydrogen and electric power, but only if both are produced from non-carbon sources. Breakthroughs in battery technology or development of methods to charge electric vehicles rapidly on the road might tip the balance toward electricity. But if better storage systems for hydrogen are achieved, hydrogen may be the better bet. Predicting now which route to pursue is difficult, but demonstrations like Sunline's will provide vital insights into the use of hydrogen as a transportation fuel, meanwhile producing some near-term benefits with minimal disruption to society.

Jane E. Brydges received an SM degree in MIT's Technology and Policy Program and an MCP degree in MIT's Department of Urban Studies and Planning in June 2000. She is now a strategist in the Corporate Strategy and Knowledge Development Group at General Motors Corporation in Detroit. Elisabeth M. Drake is associate director for new technologies at the Energy Laboratory. This research was funded as part of a broader study of future road transportation technologies by the Energy Choices Consortium, which includes a group of companies and a foundation. Further information can be found in reference 4.
In response to the renewed interest in, and opportunities for, nuclear energy worldwide, the MIT Energy Laboratory and Department of Nuclear Engineering have established the Center for Advanced Nuclear Energy Systems (CANES). Some 20 MIT faculty and staff are directly involved in CANES, which will coordinate and expand MIT activities in examining new technology options for future nuclear energy plants and fuel facilities. In addition, CANES will examine the best approaches to managing and regulating such facilities.

Directed by Professor Mujid S. Kazimi, Tokyo Electric Power Company (TEPCO) Professor of Nuclear Engineering, the center will also serve as a resource for examining emerging external ideas for improved or new energy systems. Additionally, the center will undertake educational activities, such as short courses, electronic offerings, and topical publications for a variety of audiences, including nuclear engineering and energy professionals, national and international policymakers, and interested members of the public.

Today, nuclear energy is one of the few options that can meet the growing worldwide demand for electrical power while maintaining air quality and avoiding significant emissions of greenhouse gases. Nuclear power plants, which provide nearly 20% of the world’s electricity, have operated in recent years with increasing reliability and safety. However, intensive efforts to explore innovative technology essentially ceased during the last two decades. Major improvements in the economics, safety, and reliability of nuclear plants are now possible, especially in light of revolutionary changes that have occurred in materials and information technology and the lessons provided by the operation and regulation of today’s reactors.

CANES currently has four research programs: advanced nuclear reactor technology; nuclear fuel cycle technology and policy; nuclear systems enhanced performance; and the international program for spent-fuel management. The annual funding of CANES is $3.5 million, with most of the funds provided by the Nuclear Energy Research Initiative (NERI) of the US Department of Energy, Tokyo Electric Power Company, and the Idaho National Engineering and Environmental Laboratory.

On July 13–14, the Energy Laboratory hosted a symposium entitled “The Future of Diesel: Scientific Issues,” held at MIT’s Endicott House in Dedham, Massachusetts. The symposium opened with a session addressing the question, Where are we now? Subsequent sessions focused on regulations in the United States, Europe, and Asia; where Europe and Asia are going with diesel; issues on the road to clean diesel; and health effects and risk assessment. The symposium closed with a panel discussion of diesel’s role in the future. Attendees included almost 90 scientists, regulators, and industry and public interest representatives. The symposium was sponsored by 17 organizations, among them oil companies, automotive companies, electric power companies, regulators, and academic organizations. An article describing the discussions and conclusions from the symposium will appear in the next issue of e-lab.

The workshop, “New Energy in a New Century,” was held on June 28–30 in Oviedo, Spain. An overview of changes in the electric industry was provided, with particular sessions devoted to the generation market, interconnections between regional markets, and retail sales and distribution. The workshop was well publicized by the Spanish press and drew more than 40 participants from industry, government, and academia.

In mid-June, Cambridge University Press released Markets for Clean Air: The US Acid Rain Program, a comprehensive description and evaluation of the US Acid Rain Program’s remarkably successful first three years. The book distills more than five years of CEEPR research. Over 950 copies of the book have already been sold, and reprinting is likely in 2001. The book is of particular interest now because of its relevance to climate change policy. The Acid Rain Program involved the first large-scale use of tradable emissions permits to address an environmental problem. That policy approach is now being discussed at the international level as one tool for implementing the Kyoto Protocol. The book has received glowing reviews. For example, in an extensive review in the Journal of Economic Literature (September 2000), Peter Cramton of the University of Maryland says, “Markets for Clean Air is the definitive text on the US acid rain program. The authors’ analysis is careful and convincing. The reader is rewarded with significant insights about a major environmental program... Both scholars and policymakers will have a better sense of the virtues and pitfalls of market-based regulation after reading this book.” Authors of the book are Dr. A. Denny Ellerman, Professor Paul L. Joskow, and Professor Richard Schmalensee of MIT, Professor Juan-Pablo Montero of the Catholic University of Chile, and Dr. Elizabeth M. Bailey of National Economic Research Associates, Inc. The 362-page book is available from Cambridge University Press (<http://www.cup.org/>), retail book stores, and web retailers.

Energy Laboratory researcher Marija Ilčić and John Zaborszky of Washington University have published Dynamics and Control of Large Electric Power Systems, a new book that offers an
advanced presentation of modern power systems, starting from a brief overview of their physical components through to modeling, analysis, and control concepts. This unusually comprehensive book fills a void in the existing power systems literature and can be used as a textbook as well as a major reference. The main topics covered are modeling the structure and components of a large power system, analysis of stationary and dynamic processes, and control and stabilization. Several chapters are devoted to identifying the objectives of operations and control as a function of industry structure. Examples are given for both regulated and competitive structures. Challenges such as transmission congestion provision and pricing are posed as decisionmaking problems for the first time. The 838-page book costs $175 and can be ordered from John Wiley & Sons (phone: 1-800-225-5945; fax: 1-212-850-8888; e-mail: custserv@wiley.com; World Wide Web: <www.wiley.com>).

Subra Suresh, the R.P. Simmons Professor and head of the Department of Materials Science and Engineering, will receive the Distinguished Scientist/Engineer Award from The Minerals, Metals, and Materials Society (TMS) in recognition of his long-lasting contribution to the fundamental understanding of the microstructure, properties, and performance of structural materials for industrial applications. The award will be presented during the annual TMS meeting in New Orleans in February 2001. Professor Suresh leads Energy Laboratory research on problems inherent in restructuring the electric power industry (see e-lab, January–March 1998).

PUBLICATIONS AND REFERENCES

The following publications of Energy Laboratory and related research were released during the past period or are cited as references in this issue. MIT theses may be ordered from Library Document Services, MIT, Room 14-0551, Cambridge, MA 02139-4307. Other publications may be ordered from Energy Laboratory Publications, MIT, Room E40-473, Cambridge, MA 02139-4307 only if a price is assigned and only if prepaid by check payable to “MIT Energy Laboratory.” Prices are postpaid surface mail. For air delivery, add 15% to the US, Canada, and Mexico, and 30% elsewhere. A list of publications is available on request.

Publications marked by an asterisk (*) can be found or are forthcoming on-line via the following addresses:


Instructions for ordering paper copies of the reports and working papers are also available at the above-listed sites or by telephoning 617-258-0307 for Energy Laboratory publications, 617-253-3551 for Center publications, and 617-253-7492 for Joint Program publications.

Reports and Working Papers


**Other Publications**


Takamura, H., and H. Tuller. Ionic Conductivity of Gd$_2$GaSbO$_7$—Gd$_2$Zr$_2$O$_7$ Solid Solutions with Structural Disorder. Accepted for publication in Solid State Ionics. 22 pages. 2000. $10.00


Tuller, H. Ionic Conduction in Nanocrystalline Materials. Invited and accepted for publication in Solid State Ionics. 36 pages. 2000. $10.00


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